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CFD Model for Ventilation in Broiler Holding Sheds

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Abstract:

Broiler production in Arkansas was valued at over $3.6 billion in 2013 (University of Arkansas Extension of Agriculture). Consequently, improvement in any phase of the production process can have significant economic impact and animal welfare implications. From the time poultry leave the farm and until they are slaughtered, they can be exposed to harsh environmental conditions, both in winter and in summer. After road transportation, birds are left to wait in holding sheds once they arrive at the processing plant, for periods of approximately 30 minutes to two hours. This project was interested in this holding shed waiting time during hot summer conditions. A computational fluid dynamics (CFD) model was developed using the commercial package ANSYS Fluent and used to analyze the effect of six different scenarios of varying inlet velocity and inlet temperature on the airflow, temperature, and humidity within the trailer parked in the holding shed. A temperature-humidity-velocity index (THVI) was used to assess the possible effects of local conditions on chicken welfare. Results showed that increasing airflow into the trailer module had a significant effect on reducing temperature and humidity within the module, potentially improving welfare of the poultry. While the model was too simplified to accurately compare to field measurements, this study showed the potential of CFD software to solve problems in this area. A more robust CFD model could be used to test the effects of alternative solutions such as the placement and number of cooling fans within the holding shed, making it a powerful decision making tool.

Acknowledgements:

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1. Introduction

Temperature extremes on poultry are a major cause of physiological stress (Hoxey et al., 1996). During the transport of poultry, birds can be subjected to extreme heat or cold. These conditions are concerning, because extreme temperatures are the foremost cause of dead birds on arrival (DOAs) (Kettlewell et al. 2001). The national annual averages for DOA percentages from 2000 to 2005 were between 0.35 and 0.37% (Ritz et al., 2005). Assuming an annual US production of 8.5 billion broilers, this accounts for a loss of about 30 million birds. The economic impact of such losses can be large. Heat stress in particular has been recognized as a major cause of bird mortality. During the summer months, DOA percentages can increase to over 1.0% (Hoxey et al., 1996). Even if birds are not dead, quality of meat can still be affected (Schwartzkopf-Genswein et al., 2012).

Commercial trailers for carrying chickens are composed of groups of modules, and are open to the atmosphere during summer months. Transport of poultry to the processing plant utilizes natural ventilation. When birds arrive at the killing plant, trailers are parked in holding sheds, and birds are left to wait for a period of time. The range of conditions in which the birds are able to regulate internal body temperature is the thermoneutral zone. The thermoneutral zone for broilers in transit has been found to be 8 to 18 °C (46 to 64 °F) for well-feathered broilers packed densely together, well below typical production and transport conditions (Webster et al., 1993). Data taken from previous studies in northwest Arkansas has shown holding periods ranging from 90 to 130 minutes (Liang and Liang, 2015). Holding sheds utilize natural ventilation and fan banks in a variety of arrangements for cooling. Fans placed in front of the trailer modules force air through the modules, providing a convective cooling effect on the birds. Tunnel ventilation systems are commonly used in poultry houses for this reason. A common goal for these systems is to generate air velocity of 3.0 m/s (Dozier et al., 2005). Research has shown that 1 m/s airflow will provide a 1°C cooling effect, while a 2 m/s will provide a 3.7 °C cooling effect (Huffman, 2000). The environment of a poultry house and that of a poultry trailer are not identical however, and packing densities are different. For ventilation of a poultry trailer, Kettlewell et al. (2000) proposed a ventilation rate of 3 m^3/s, corresponding to air velocities of 1 m/s.

Currently, the operation of fans and cooling protocol in poultry holding sheds is not supported by engineering research, and practices vary from plant to plant. For example, at George's Inc. in Springdale, Arkansas, the fans are turned on at 70 °F, but this is a practice based only in tradition. The effectiveness of different fans and fan configurations under varying environmental conditions is not well understood. A study by Ritz et al. (2005) cited the need for future investigation into the number and configuration of holding shed fans, the benefit of evaporative cooling capabilities, and attention to trailer rotation.

A field based study testing various cooling scenarios would be costly and time consuming. Therefore, a method to predict the thermal environment of a variety of poultry trailer cooling configurations exposed to a range of environmental conditions is desirable. In this regard, computational fluid dynamics (CFD) can be utilized. Computational fluid dynamics (CFD) is a numerical method to solve a variety of problems involving fluid flow. Numerical modeling and commercial CFD programs are becoming more popular due to increased computing power and ease of use. ANSYS Fluent 16.0 software was used for all CFD simulations in this project. ANSYS software is widely used for a variety of engineering applications, including the optimization of heat transfer through industrial equipment and buildings and structures. Fluent is a program developed by ANSYS for solving problems involving fluid flow, and has been applied in numerous studies in livestock housing and transport. Some of the features of ANSYS Fluent include (from www.fluent.com)

- Modeling of viscous and laminar flows
- Steady state and transient problems
- Multiphase flow to model particles
- Heat transfer and radiation

For this study, adequate knowledge of the problem domain and accurate implementation into Fluent was necessary. Following are the objectives of this study and a brief introduction to CFD software and its applications in similar problems.

1.1 Objectives and Constraints

The objectives for the CFD analysis are as follows:

- Develop a computational model that can accurately predict the interior environment of a fully loaded poultry trailer module within a holding shed under varying environmental conditions and ventilation rates
- Identify areas of concern (high thermal stress) within poultry trailers during a variety of ventilation and environmental conditions
- Capability to test alternative cooling strategies using the CFD model
- Evaluation of different ventilation schemes under varying outdoor temperatures

This report can be considered a preliminary study into the larger goal of modeling an entire poultry trailer, and will serve as proof of concept for the CFD method for modeling this problem. Due to the limits imposed by the ANSYS Student license used, only a section of the entire poultry trailer (a single module in this case) could be modeled. Interactions between adjacent modules that might be significant could not be tested. Additionally, fans were not explicitly modeled nor were the far field boundaries. Rather, air velocities normal to the boundary were specified at the inlets of the modules to estimate the effects of the fans, and air outlets were specified on all sides where air left the module. Due to these number of simplifications, CFD results were not validated with field measurements.

This report is in conjunction with a larger study currently undertaken by Dr. Yi Liang of the University of Arkansas Biological Engineering Department. Further objectives of the complete study include characterizing the thermal microenvironment on broiler trailers during both transport and holding shed times during three seasons of the year, and the development of an electric chicken to quantify heat exchange of broiler chickens within trucks (Liang and Liang, 2015).

1.2 Literature Review

The basic concept of CFD consists of a series of steps (Norton et al., 2007):

- Creation of a model geometry
- Discretization of this geometry into a finite number of elements (meshing)
- Specification of cell zone conditions and boundary conditions at surface/zone interfaces
- Application of partial differential equations for conservation of mass, momentum, and energy within each element
- Iterative calculations of the conservation equations
- Analysis of results and validation

The conservation equations used for CFD are the equations of continuity (1), conservation of momentum (2), and conservation of energy (3). For an incompressible fluid with isothermal properties they are:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = 0 \qquad (1)$$

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + \rho g_i + F_i \qquad (2)$$

$$\frac{\partial}{\partial t}(\rho cT) + \frac{\partial}{\partial x_j}(\rho u_j cT) - \frac{\partial}{\partial x_j}\left(K\frac{\partial T}{\partial x_j}\right) = S_T \qquad (3)$$

where ρ: fluid density (kg m^{-3}); t: time (s); x, x_i, x_j: length components (m); u_i, u_j: velocity component (m s^{-1}); p: pressure (Pa); τ_{ij}: stress tensor (Pa); g_i: gravitational acceleration (m s^{-2}); F_i: external body forces in the i direction (N m^{-3}); c: specific heat (W kg^{-1} K^{-1}); T: temperature (K); K: thermal conductivity (W m^{-1} K^{-1}); S_T: thermal source term (W m^{-3}) (Bustamante et al., 2013).

Use of CFD in agricultural engineering has become more prevalent in recent years due to greater available computing power. Simulations are now faster and more accurate, making CFD a valuable tool in a wide range of applications. The advantages of CFD are numerous. Researchers can examine a much greater number of points within a problem domain when compared to field measurements (Blanes-Vidal et al., 2008). CFD enables quick testing of multiple design alternatives, making it a powerful, less expensive and efficient decision-making tool. Many CFD programs provide visual representation of results, such as contours of temperature and pressure and vectors for air velocity. Due to the importance that ventilation rate and air temperature serve in the thermal comfort of farm animals within their environments, CFD and its capabilities can be very relevant. Early applications of CFD modeled the indoor environment of greenhouses. Building on these studies, many publications have used CFD in studies of indoor conditions of swine, poultry, and livestock houses and carriers. In addition, CFD has been used to model polluting emissions from livestock houses. Several of these studies are summarized below.

Dalley et al. (1996) attempted to use numerical modeling to characterize the thermal environment that chickens are exposed to during commercial transport. More specifically, temperature, humidity, and ventilation rate within the transport trailer were calculated. Data from a series of full-scale wind tunnel experiments was used to input boundary conditions in a CFD model. A commercial CFD model was not used; rather, a numerical model based on the conservation of mass and energy was developed. While not as powerful and full featured as CFD models that exist today, the computer model did predict temperature and relative humidity in the trailer over time and space, and showed sensitivity to external environmental conditions and wind direction. The study concluded that computer modeling could be used as a tool to estimate the internal environments of different trailer journeys and configurations.

Early uses of commercial CFD software were applied to greenhouse environments. Kacira et al. (1998) used the commercial CFD program Fluent V4 to predict ventilation for different configurations of inlets and outlets in a greenhouse. This early study showed the importance of computer power in CFD studies, as researchers were limited in the size of the computational domain and calculation times were on the scale of 8 to 24 hours. Nonetheless, the researchers were able to identify a specific inlet configuration for ideal ventilation rates based on results of the model.

Similar to research on greenhouses, later studies attempted to predict ventilation rates within livestock houses. A research paper by Blanes-Vidal et al. (2008) applied CFD to quantify ventilation rates within a poultry house to identify possible conditions dangerous to the thermal comfort of birds. The CFD code Fluent 6.0 was used. Boundary conditions for inlets and outlets were determined from on-site measurements. Four different boundary condition scenarios were tested. Results from the simulations were validated using wind speed and temperature measurements within an actual poultry house. According to the authors, simulated air results were "a reasonable estimation of velocities in a commercial poultry building" (Blanes-Vidal et al., 2008). CFD simulations over estimated mean air velocities at bird height by 0.18 m/s (0.54 m/s for the simulation compared to 0.36 m/s from measurements) (Blanes-Vidal et al., 2008). The authors concluded that CFD can provide "useful information about the actual airflow in commercial poultry buildings." However, this study did not include the presence of live chickens and their thermal effect within the model, making its applicability to this study somewhat limited.

A similar study by Bustamante et al. (2013) applied the CFD code Fluent to mechanically ventilated poultry houses. Different set ups for number of fans and inlet openings were tested. Results from CFD simulations were validated with a multi-sensor system. CFD results showed close agreement with experimental data (mean of air velocity values was 0.60 ± 0.56m s^{-1} for CFD techniques and 0.64 m s^{-1} for direct measurements).

Besides results for air ventilation and temperature and humidity conditions, several studies have used CFD to model gaseous emissions from agricultural houses. Many CFD programs have the ability to model species transport. Pawar et al. (2007) used a 2D model in the CFD code Fluent to model the spread of virus particles from a poultry house. Two ventilation schemes were tested, and one was found to better limit the spread of contaminants downwind. However, CFD simulations were not validated with experimental data.

Ammonia is one of the most harmful pollutants from agriculture houses. A study by Rong et al. (2015) used CFD to model ammonia emissions from a swine house. CFD also has been used to simulate gas mixing within swine houses (Stikeleather et al., 2012).

Inclusion of animals in CFD models has fallen into two categories. Some studies have used simple geometric shapes to simulate the impact of animal forms on airflow, and also included models for animal heat and moisture production. Conversely, other studies have utilized porous media to represent the animal occupied zone (AOZ) in order to simplify the model and increase the speed of calculations.

Pawar et al. (2007) represented hens as blocks specified as walls in the CFD model Fluent. The walls were given a boundary condition of constant heat flux to model heat generated by the hens. The heat flux calculated was equal to the basal metabolic rate of the hens. However, in actuality, heat loss from animals is dependent on the air temperature, wind speed, coat thickness, and long wave and solar radiation (Turnpenny et al., 2000).

Norton et al. (2010) attempted to model convection and radiation from calves in a CFD study as a function of the external environment. The authors developed a zero dimensional calf heat model (0d-CHT) using a comprehensive energy balance evaluated with MATLAB software. Additionally, a CFD model for calf thermoregulation (CFD-CHT) was made in the CFD program STAR-CCM+. Results for the models were validated with wind tunnel experiments and heat transfer studies for living calves. Wind tunnel tests showed good agreement with both models. Next, the 0d-CHT and CFD-CHT models were combined to form a simplified representation of calf heat flux (CFD+0d-CHT) that modeled variable partitioning of convective and radiative heat loss. The CFD+0d-CHT model was termed the dynamic convective heat flux boundary condition model (DBM). Authors then compared the DBM with a calf model for predetermined convective heat flux boundary condition (PBM) in a commercial calf building using STAR-CCM+. The PBM assumed a 50:50 partitioning of convective and radiative heat loss. Calves were represented as half spheres, and convection heat transfer from the coat and radiative heat transfer were considered as a function of air temperature. Results from the CFD experiments showed that the environment within the livestock building did not vary significantly between DBM and PBM models for three different tests. The study concluded that for wind driven environments, a model taking into account thermoregulation for calves (the DBM model in this case) was not necessary, as it was unnecessarily complicated and time consuming (Norton et al., 2010).

A later study by Norton et al. (2013) showed the effectiveness of modeling cattle as a DBM type model for predicting the temperature and relative humidity in mechanically and naturally ventilated livestock transportation trailers. Cattle were modeled as half ellipsoids with varying heat and moisture loss based on environmental temperature (Norton et al., 2013). STAR-CCM+ software was used. A boundary condition of constant outward velocity represented the fans in the mechanically ventilated trailer, while the naturally ventilated condition used a pressure outlet and relied on internal buoyancy generation for air flow. Results showed that mechanically ventilated trailers had less homogenous conditions, a fact that could be concerning in winter months, when low ventilation rates could cause poor air quality in some parts of the trailer (Norton et al., 2013).

Another method for modeling animals within the computational domain is to designate the animal-occupied zone (AOZ) as porous media. The benefits of using porous media are significantly reduced mesh size and improved calculation speed and accuracy. The porous media should have resistance corresponding to the size and packing of animals, as well as a heat generation component. Wu et al. (2012) used a porous model to represent the AOZ in a study for determining air exchange rates within a naturally ventilated dairy cattle building. Resistance coefficients for the porous media were found using a sub-model. The sub-model consisted of four model cows arranged within a part of the building. The pressure drop across the domain for numerous air velocities was then found using CFD to quantify a resistance coefficient to be used in the porous media model.

Rong et al. (2015) used porous media to model the slatted floors of a pig house in a study on ammonia emissions from underground manure storage. The porous media model was not able to predict air speed accurately above the floor; however, results for ammonia emissions from the porous media model were comparable to results from a slatted floor CFD model.

After extensive literature research, it was determined that no prior studies modeling the environment within poultry trailers using CFD existed. For the development of a CFD model in this project, various aspects of prior studies were utilized and incorporated into the model design.

2. Materials and Methods

2.1 Location

The area used for model creation in this study was George's Inc., a poultry processing plant in Springdale, Arkansas. Poultry trailers are brought into holding sheds underneath a sloping metal roof but open at the sides. On the poultry trailers are rows of modules in which chickens are contained. Typically, 10 or 11 rows are lined up going the length of the trailer, and one module is stacked on top of another, for a total of 20 or 22 modules. The module structure is made of an aluminum frame, with five fiberglass floors, dividing each module into five tiers. Chickens are loaded into the tiers of the module through a set of spring-loaded doors. The front, back, and opposite side consist of a metal latticework that does little to obstruct airflow. A picture of a poultry module used by George's trucks is given in figure 2.1, along with a schematic describing module dimensions (figure 2.2).

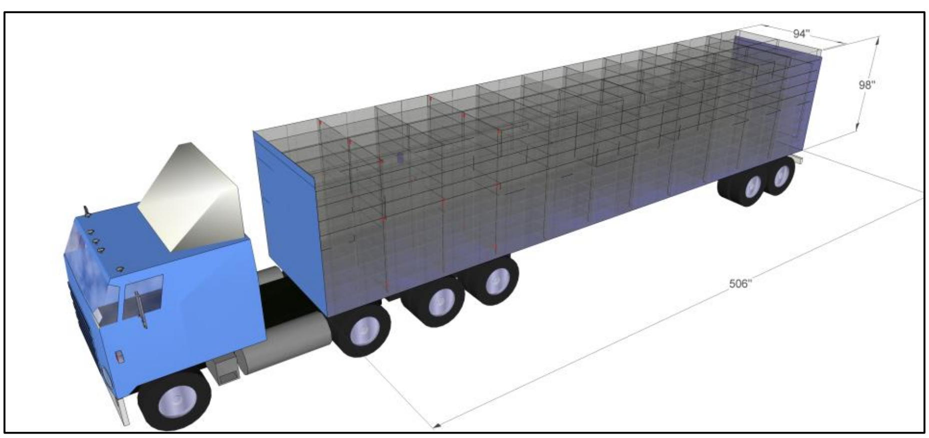

Figure 2.1: Modules arranged on trailer

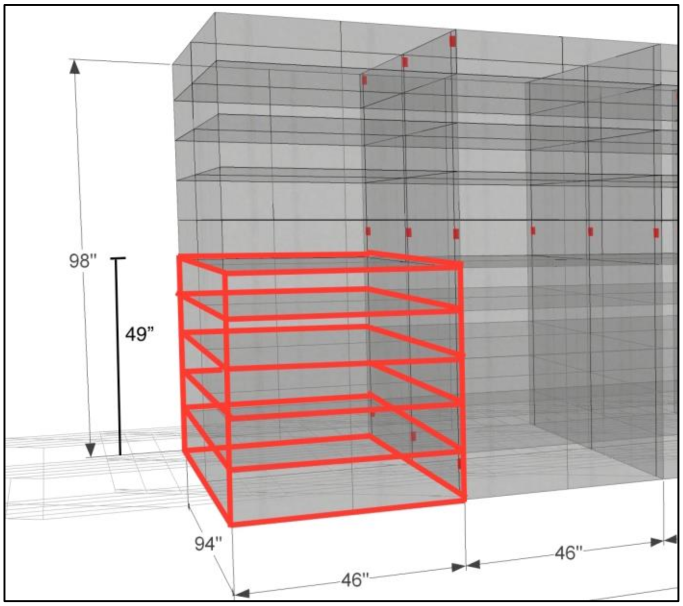

Figure 2.2: Module dimensions. Four modules are shown. Red outlines show one module divided into five tiers

Within the cooling sheds at the study plant, the trucks park two wide next to a series of fan banks. Fans measured at the site were 54 inches in diameter. Typically, six fans are arranged in a row, with fan rows placed on opposite sides of the shed blowing air onto the adjacent trailers (figure 2.3). The fans at the site were positioned 88 inches from the ground to the bottom of the fan and 50 inches horizontally from the trailer, at a slight downward angle.

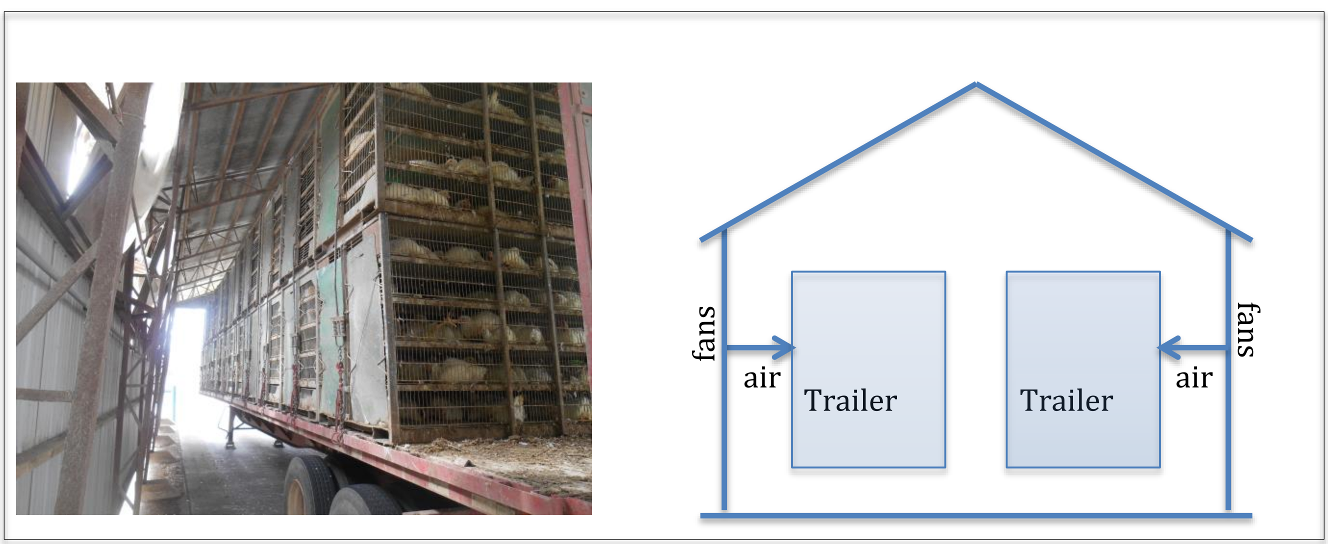

Figure 2.3: Trailer set up within holding shed

2.2 Set-up of the CFD model

2.2.1 Geometry and Meshing

Due to the complexity and limitations imposed by the ANSYS Student License, the area surrounding the trailer was not modeled, nor was the fan, and only a single module was used in simulations. A simplified representation of a single trailer module was designed using ANSYS Design Modeler, the 2D and 3D solid modeler included within ANSYS Workbench. Model dimensions were 46 inches wide, 49 inches tall, and 94 inches in depth, matching those of an actual module. For the CFD model, wire meshing and aluminum frame supports was not included on the faces of the module, since it was assumed that these elements did not have a significant effect on airflow within the module. This greatly decreased the complexity of the model and the amount of meshing required. Within the module, chickens were represented as spheres with diameter of 8.5 inches, as shown in figure 2.4. This seemed a reasonable approximation for a chicken body, as the skin surface area of a chicken can be approximated by the following equation (Aerts and Berckmans, 2004):

$$A_s = 0.081W^{0.667} \tag{1}$$

where A_s is skin surface area (m^2) and W is body mass (kg). For a typical 2.5 kg bird, this equates to

$$A_s \approx 0.15\, m^2 \tag{2}$$

A sphere with surface area of 0.15 m^2 will have radius of approximately 0.109 meters. A radius of 4.25 inches was used as a reasonable approximation. The spheres were arranged in the module in loading densities for chickens according to information provided by George's Inc. For 2.5 kg birds, loading density was 220 birds/module. Meshing was done in the built in pre-processor within Fluent. The total number of elements in the mesh was 503,810, and the number of nodes was 114,661. Quality of the mesh was checked within Fluent, and deemed acceptable by the program.

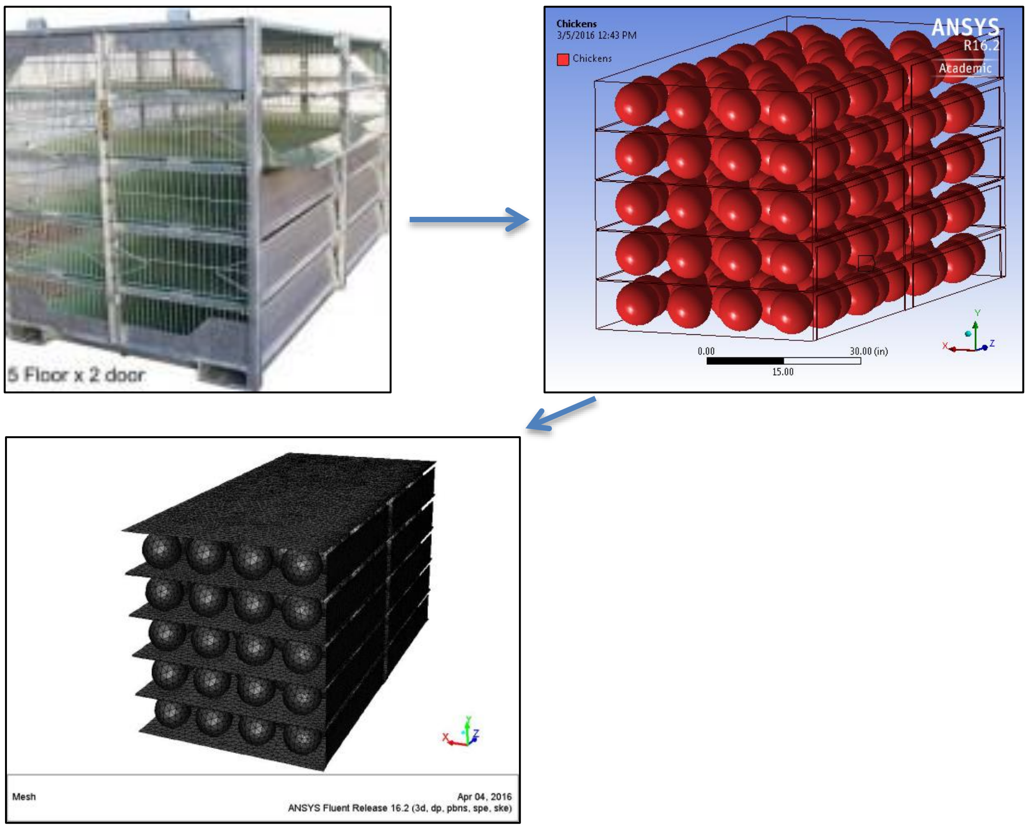

Figure 2.4: Geometry and meshing of the trailer module

2.2.2 Boundary Conditions and Computational Models

Boundary conditions were defined for the walls of the module, the floors, the chickens, and inlets and outlets. The walls, doors, and floors of the module were given no-slip and adiabatic (heat flux = 0) conditions. The chickens were represented as spherical walls with a constant heat flux approximating heat generation by the birds (Pawar et al, 2007). Total heat production by broilers was estimated to be 7 W/kg (Xin et al., 2001). For a 2.5 kg bird, and dividing by the surface area of the bird, this equates to $7\frac{W}{kg} * 2.5kg \Big/ 0.15m^2 = 116.67\frac{W}{m^2}$

However, not all of the heat produced by the birds enters the air as sensible heat. A study by Kettlewell et al. (2000) found that of heat produced by poultry on a transport trailer, 62% was sensible and 38% was latent. The heat flux leaving the chickens was input as a constant $\frac{116.67W}{m^2} * 0.62 = 72.3\frac{W}{m^2}$.

No literature value for the roughness of poultry feathers could be found. The roughness height of the chickens was estimated to be 0.25 inches.

To model the moisture produced by the birds within the trailer, a constant H_2O source term was added to the air cell zone. This constant was determined to be equivalent to the latent heat generated by the birds. For a total heat production of 116.67 W/m^2, assuming 38% of heat generated is latent, the amount of latent heat produced is $\frac{116.67W}{m^2} * 0.38 = 44.3W/m^2$. The volume of air in the module is the total volume minus the volume of floors and birds. The total moisture produced by all birds in a module, in terms of per volume air, is thus

$$\frac{44.3W}{m^2} * \frac{0.15m^2}{bird} * 220\frac{birds}{module} * \frac{1module}{2.2\,m^3air} * \frac{1kJ}{1000W \cdot s} * \frac{1kgH_2O}{2264.76kJ}$$

$$= \frac{2.93\ \times 10^{-4}kgH_2O}{m^3air \cdot s}$$

Inlets were specified at the side of the module facing the fan, or the “front” of the module. These inlets were given constant velocity boundary conditions and constant air temperature based on the scenario. Outlets were specified where the air leaves the module, which were the back and two side faces of the module. On the doors side of the module, air exited through the gaps between doors and floors. All outlets were given pressure boundary conditions of atmospheric pressure and temperature equal to ambient temperature. Relative humidity of the air coming through the inlets was set at a constant condition of 50% RH for all simulations, a reasonable approximation of average afternoon humidity in Arkansas during the summer months. The boundary conditions within the model are summarized below.

<u>Cell Zone and Boundary Conditions:</u>

- Walls, doors, and floors: no-slip, adiabatic
- Chickens: no-slip, constant heat flux = 72.3 W/m^2, roughness height = 0.25 inches
- Inlets: Constant velocity, constant temperature
- Outlets: Constant pressure = 0 pa gauge
- Air: H_2O source term = 0.000293 kg H_2O/m^3 air • s

Six scenarios using two different inlet velocities and three different ambient temperatures were tested to assess the impact of different inlet velocities and outdoor temperatures on the environment within the poultry module. Inlet velocity conditions were based on typical values seen from field measurements, and temperatures based on those typical in summer months in Northwest Arkansas. Boundary conditions for the six scenarios are summarized in table 2.1.

Table 2.1: Inlet Conditions Tested

Scenario	Inlet Temperature (°F)	Inlet Velocity (m/s)
1	80	1.5
2	80	3
3	90	1.5
4	90	3.0
5	95	1.5
6	95	3.0

Pressure based solver was used in the simulation. The airflow within the module was assumed turbulent, which is common among ventilating flows (Norton et al, 2010). The standard k-epsilon model was used with standard wall functions as it has been applied numerous times in similar applications (Bustamente et al, 2013; Norton et al, 2010; Pawar et al, 2007). Since similar studies had utilized radiation (Norton et al., 2013), the surface to surface (S2S) radiation model was used, as it is the simplest model for radiation. The S2S radiation model accounts only for radiation transfer between surfaces, which are considered to be gray and diffuse (Fluent User's Guide). Emissivity of aluminum door and wall surfaces was specified as 0.1, chicken surfaces was specified as 0.95, and the fiberglass floors were given an emissivity of 0.75. The species transport model was used to account for humidity. The species mixture was defined for the air zone as a water vapor mass fraction within the air. The mass fraction of water vapor coming into the module and moisture produced within the module were defined earlier in the boundary conditions. A summary of the solution methods uses for simulations is given below.

Solution Methods:

- Pressure-Velocity Coupling: SIMPLE
- Gradient: Least Squares Cell Based
- Pressure: Second Order
- Momentum: Second Order Upwind
- Turbulent Kinetic Energy: Second Order Upwind
- Turbulent Dissipation Rate: Second Order Upwind
- H_2O: Second Order Upwind
- Energy: Second Order Upwind

Simulations were run in steady state until residual values of 1×10^{-3} for continuity, x-velocity, y-velocity, z-velocity, k, h_20; 3×10^{-6} for energy; and 5×10^{-3} for epsilon.

2.3 The THVI

To contextualize the results and their effect on chicken welfare, a temperature-humidity-velocity index (THVI) was employed (Tao and Xin, 2003). The THVI, developed empirically, attempts to determine the effects of varying environmental conditions on the thermal comfort of broilers. The THVI can be expressed as (Tao and Xin, 2003)

$$THVI = (0.85t_{db} + 0.15t_{wb}) * V^{-0.058}\ (0.2 < V < 1.2) \qquad (3)$$

Where t_{db} is the dry bulb temperature in degrees Celsius, t_{wb} is the wet bulb temperature in degrees Celsius, and V is the air velocity in meters per second.

Conditions leading to a core body temperature increase of < 1.0°C were classified as normal, 1.0°C-2.5°C as alert, 2.5°C-4.0°C as danger, and > 4.0°C as emergency states.

A body temperature increase of 4°C-5.0°C is likely to cause chicken mortality (Tao and Xin, 2003). For a certain set of local environmental conditions, the following equations for exposure time (ET) quantify the time in minutes for a chicken exposed to these conditions to reach the corresponding states. These equations are

For 1.0°C increase:

$$ET = 2 \times 10^{29} \times THVI^{-17.68} \tag{4}$$

For 2.5°C increase:

$$ET = 4 \times 10^{13} \times THVI^{-7.38} \tag{5}$$

For 4.0°C increase:

$$ET = 3 \times 10^{11} \times THVI^{-5.91} \tag{6}$$

3. Results and Discussion

3.1 Temperature, Velocity, and Humidity Results

Local conditions at 14 points within the module were evaluated for temperature, air velocity, and relative humidity. These points are described in the table 3.1 and figure 3.2.

Table 3.1: Data Points for Analysis

Point	Description	Coordinates (x,y,z) (width, height, length)
1	Front, door side, bottom	2,3,2
2	Front, open side, bottom	44,3,2
3	Front, center, middle	23,26,2
4	Front, door side, top	2,46,2
5	Front, open side, top	44,46,2
6	Middle, door side, bottom	10,13,47
7	Middle, open side, bottom	36,13,47
8	Middle, door side, top	10,33,47
9	Middle, open side, top	36,33,47
10	Back, door side, bottom	2,3,92
11	Back, open side, bottom	44,3,92
12	Back, center, middle	23,26,92
13	Back, door side, top	2,46,92
14	Back, open side, top	44,46,92

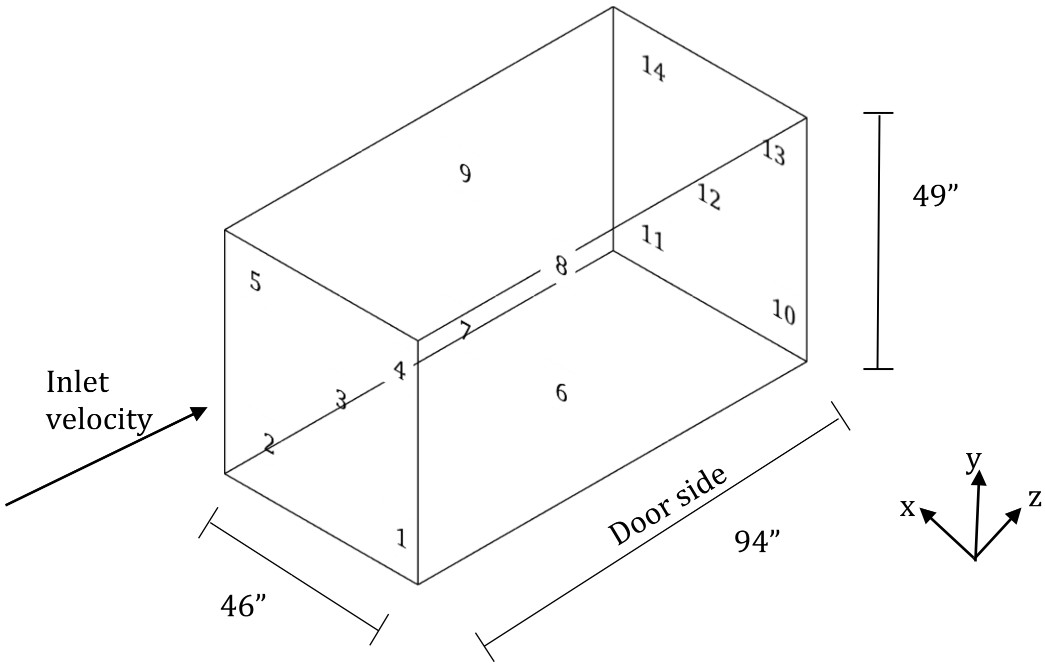

Figure 3.1: Points selected for data analysis

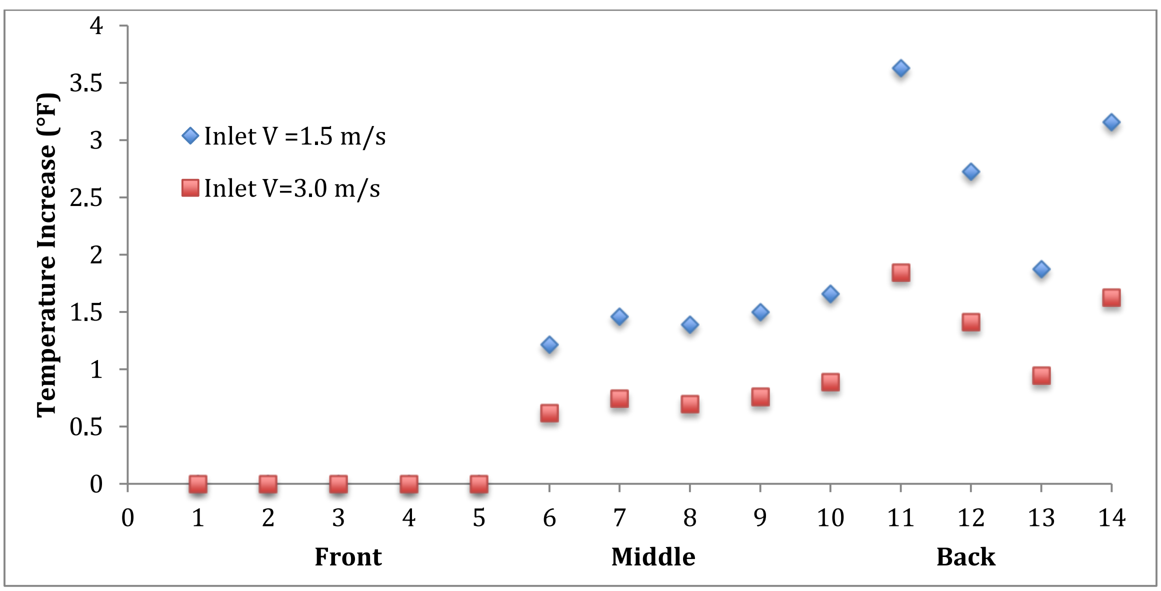

Figure 3.2: Rise in temperature throughout the module

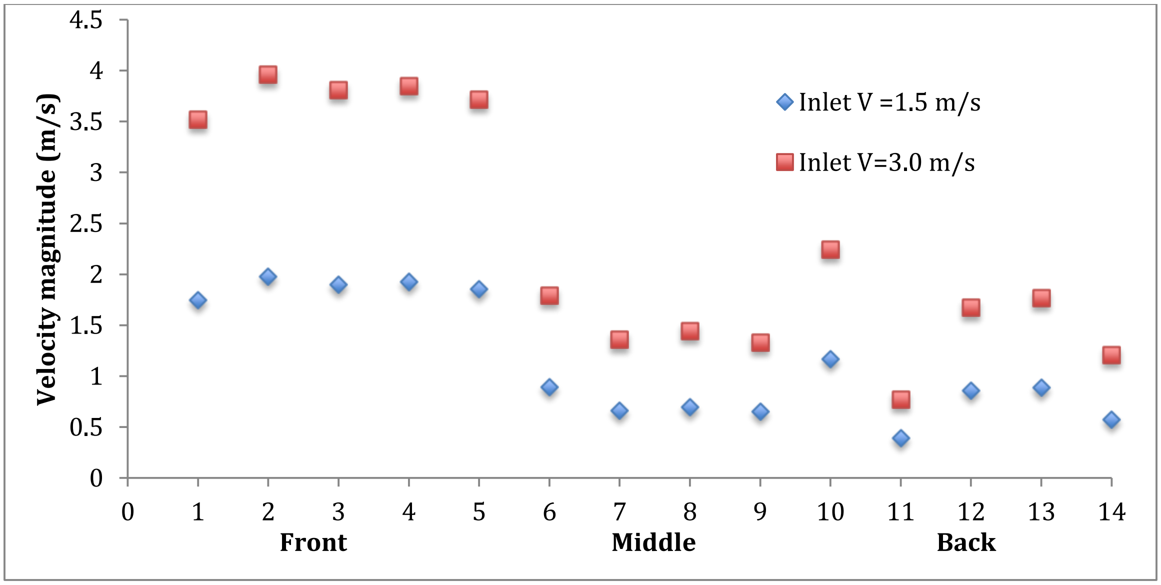

Figure 3.3: Air velocity throughout the module

Simulations resulted in expected trends for air temperature, air velocity, and relative humidity. Figure 3.2 shows the rise in air temperature above ambient for different points within the module. For points located near the inlet, temperature was unchanged. For points located in the middle plane of the module (6-9), temperature increased approximately 1.2 °F - 1.5 °F and 0.6 °F – 0.8°F for air velocities of 1.5 m/s and 3.0 m/s, respectively. For points located in the back plane of the module (10-14), temperature increased approximately 1.7 °F – 3.6 °F and 0.9 °F – 1.8°F for air velocities of 1.5 m/s and 3.0 m/s, respectively. In all cases, air in the back of the module would have longer residence time and longer exposure to heat produced by birds, causing increased temperatures.

Increasing inlet air velocity resulted in a cooling effect throughout the module. An increase in inlet air velocity from 1.5 m/s to 3.0 m/s led to a decrease in temperature of approximately 0.6 °F – 0.8 °F for points in the middle of the module, and a decrease of approximately 0.8 °F – 1.8 °F for points in the back of the module. Increasing air velocity had larger effects for air temperatures farther from the inlet.

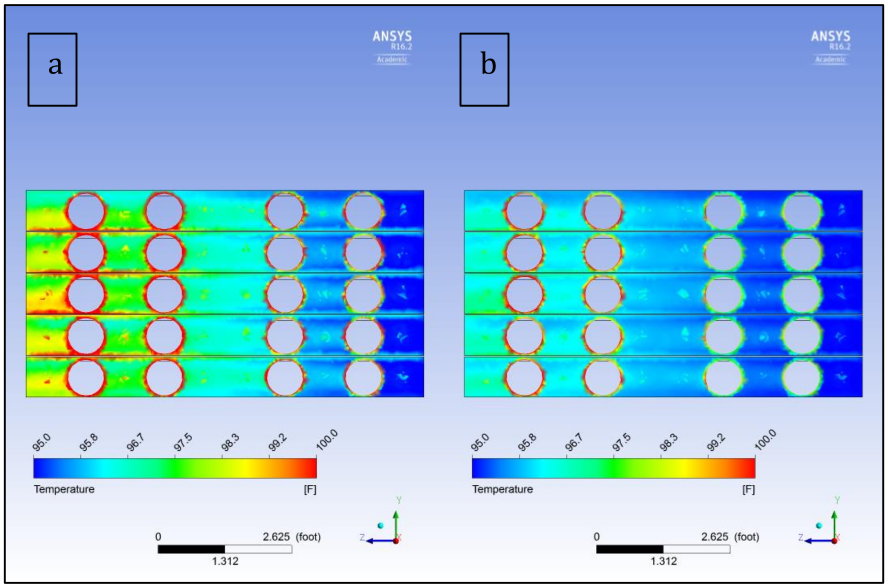

Figure 3.4: Contours of air temperature for ambient temperature of 95°F and inlet air velocity of 1.5 m/s (a) and air velocity of 3.0 m/s (b). Air enters through the right of the planes and moves left through the modules, in the z direction

Figure 3.4 shows side contours of temperature for the two inlet velocities with ambient conditions of 95 °F. The plane was cut out of the middle of the module, and is an x-y plane normal to the face of the inlet. Air entered through the right of the planes, and flowed toward the back and out the back and side outlets. Holes in the plane are due to the presence of chicken models at those locations. Contours showed that an increase in inlet air velocity was most effective at reducing temperatures toward the back of the module. The air flowing through the module acted as a form of forced convection; air having a higher velocity has a higher coefficient of convection, resulting in a greater removal of heat. The model shows that heat produced by the birds will be better dissipated by higher air velocities.

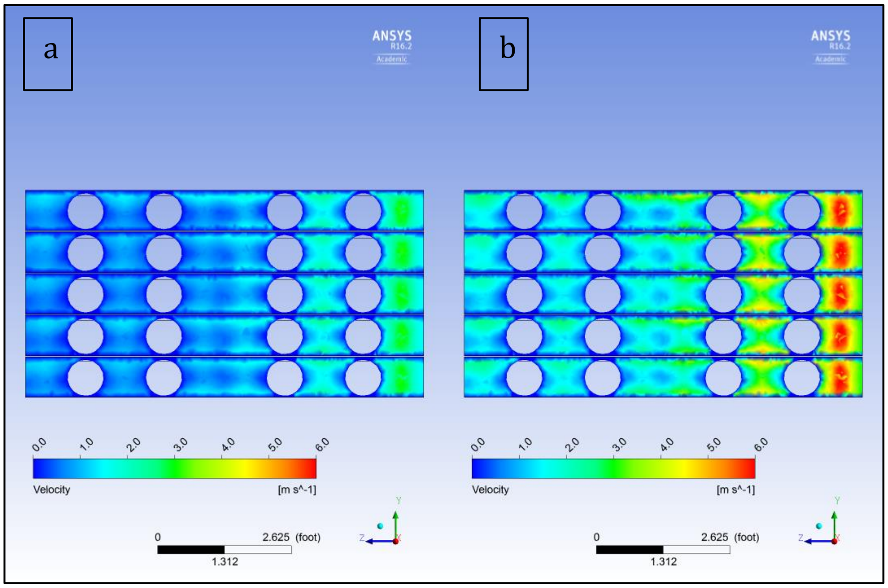

Figure 3.5: Contours of air velocity for inlet velocity of 1.5 m/s (a) and 3.0 m/s (b). Air enters through the right of the planes and moves left through the modules

Side contours of air velocity are shown in figure 3.5. Velocity magnitude increased as air encountered the chicken models. Maximum air velocities of 3.9 m/s and 7.8 m/s were calculated for inlet air velocities of 1.5 m/s and 3.0 m/s, respectively. The increase in air velocity is most likely due to a change in direction and a rotational velocity for air vectors predicted by the turbulence model, resulting in a greater magnitude of velocity. Additionally, the principle of mass continuity states air velocity will increase as air is squeezed into more narrow channels and cross sectional area decreases. Even towards the back of the module, air with inlet velocity of 3.0 m/s had air velocities significant enough to have a cooling effect. Greater turbulence and static pressure experienced by the chickens can be expected for higher inlet air velocities. A top view of air velocity vectors gives a better idea of how air moves through and exits the trailer module (figure 3.6).

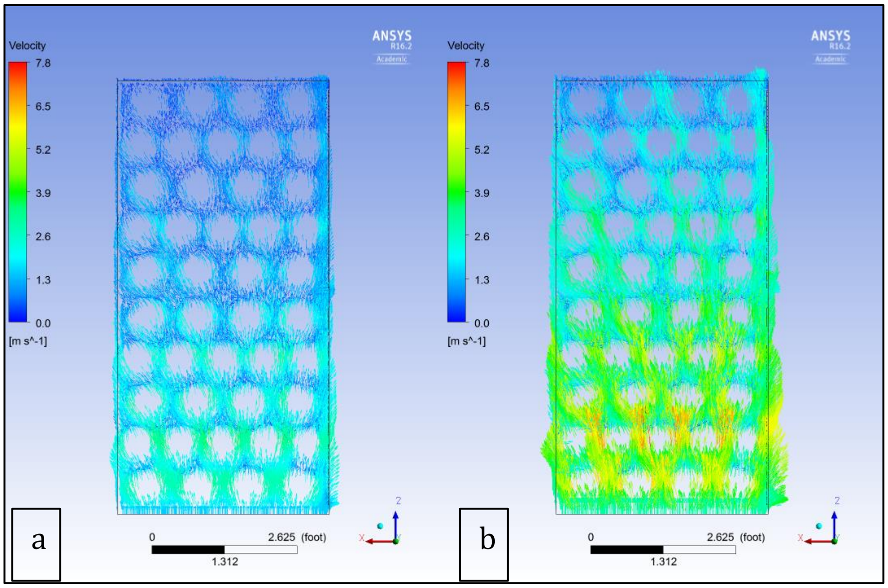

Figure 3.6: Air velocity vectors for inlet velocity of 1.5 m/s (a) and 3.0 m/s (b), top view. Air enters at the bottom of the planes and moves upward, in the z direction

Airflow also acted as a method to carry away moisture produced by the birds. At higher inlet air velocity, less buildup of moisture within the model was seen. Figure 3.7 shows the mass fraction of water in air at selected points within the module for ambient air temperature of 95 °F and ambient relative humidity of 50%. Mass fraction of water within the model increased further from the inlet. Since moisture was modeled as being produced at a constant rate, air that had longer residence time within the module would have higher moisture content. Since air with greater velocity would exit the module faster, it is expected that it would also have less buildup of moisture (figure 3.9). However, an increase in air temperature will also lead to a decrease in relative humidity, and air temperatures have been shown to be higher in cases with lower inlet velocity and at points further from the inlet. Moisture production was not significant enough relative to temperature rise to increase relative humidity through the back of the module, so relative humidity actually decreased further from the inlet.

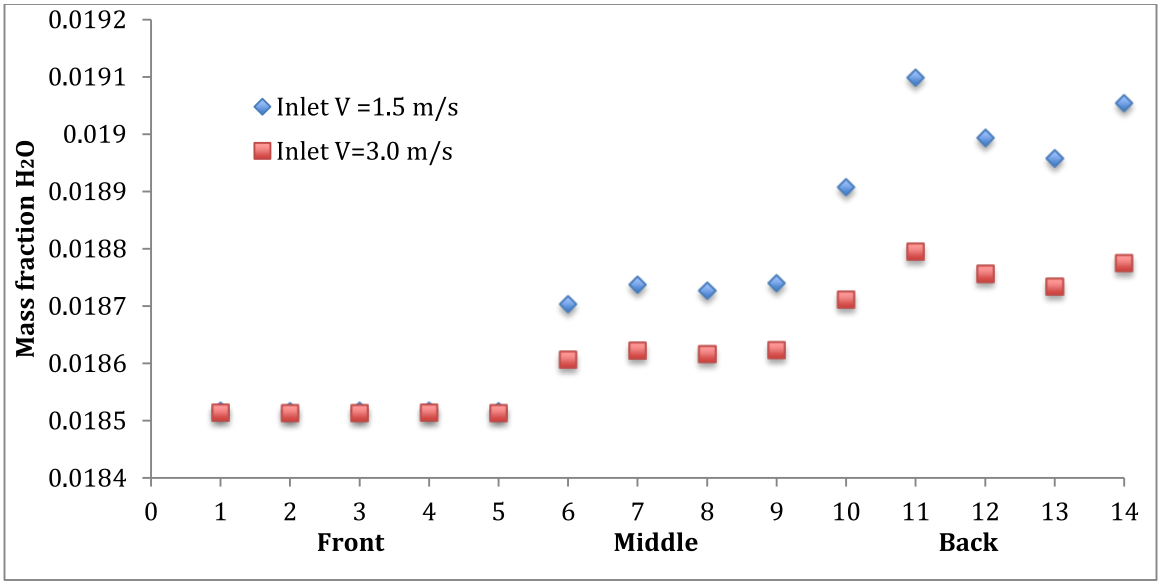

Figure 3.7: Mass fraction of H_2O throughout the module with ambient conditions of 95° F and 50 % RH (0.01851 kg H_2O/kg air)

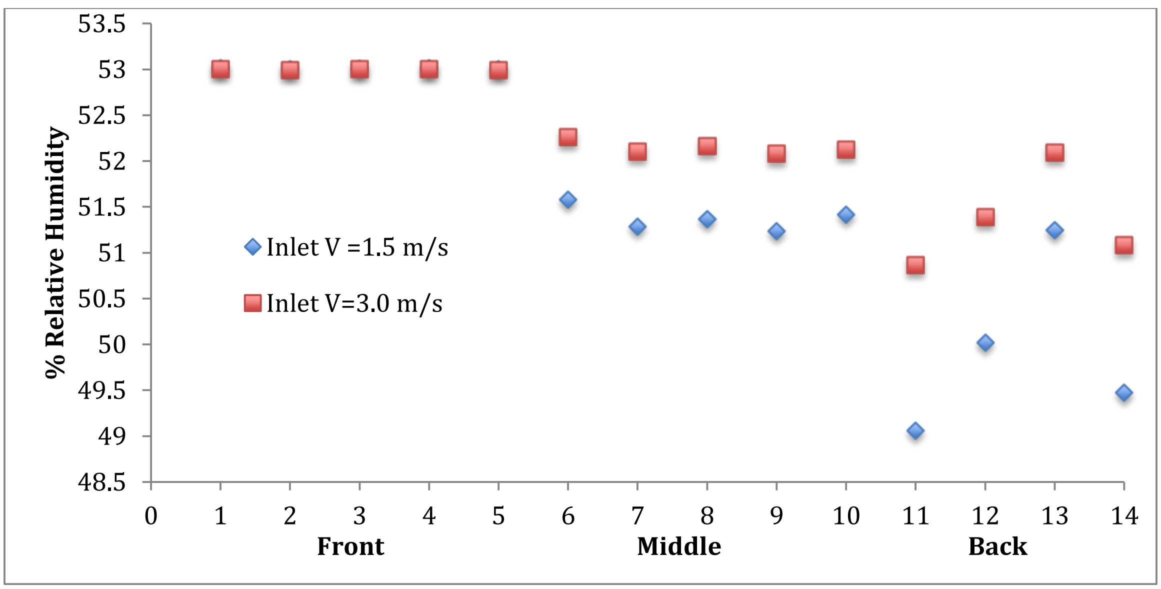

Figure3.8: RH of air throughout the module with ambient conditions of 95° F and 50 % RH

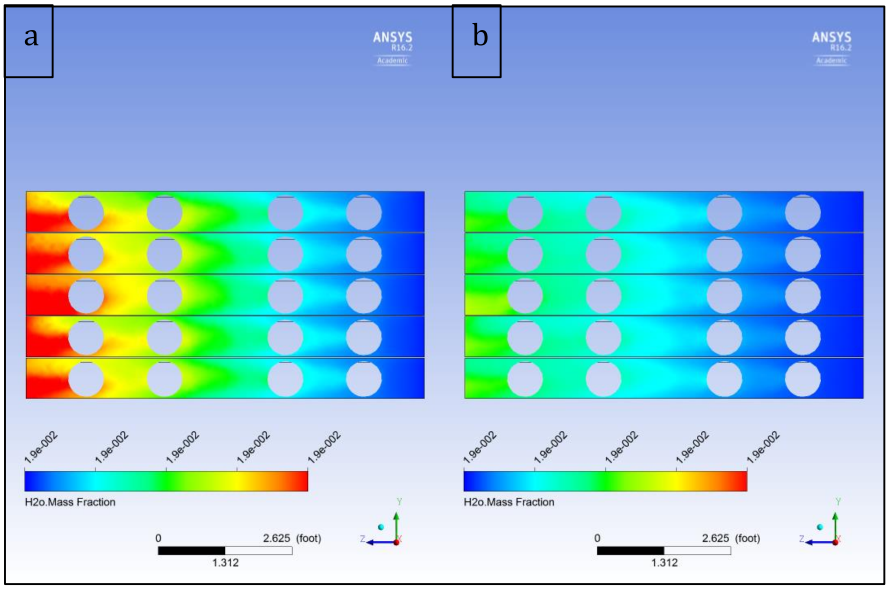

Figure 3.9: Side contours of H_20 mass fraction for ambient temperature of 95° F, 50% RH, and inlet velocity of 1.5 m/s (a) and 3.0 m/s (b). Air enters the through the right of the planes and moves in the z direction

Since the module is not symmetrical on both sides, with one side open to the air and the other having a number of aluminum doors, variations in temperature and air velocity across the plane of the module normal to the incoming air velocity would be likely.

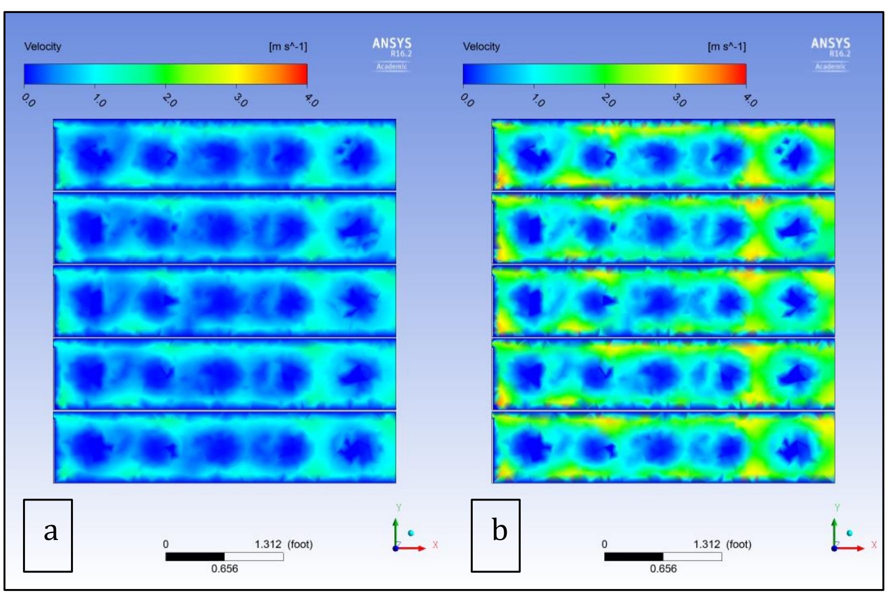

Figure 3.10: Velocity contours for middle plane normal to inlet air of 1.5 m/s (a) and 3.0 m/s (b). Left sides of each module are the door sides.

Figure 3.10 depicts how air velocity varies across a plane normal to inlet velocity. The plane lies 57 inches away from the inlet in the direction of airflow. Air velocity next to doors on the left side of each module and air velocity near to floors was reduced to zero due to the no-slip boundary conditions imposed on these surfaces. This caused an increase in local temperature near to floors (figure 3.11); however, this trend was not observed for air near doors. Air passing near to doors is squeezed into a smaller volume, resulting in higher velocities and lower temperatures. In general, temperatures were not significantly different for air zones on opposite sides of the module. Circular spots of low velocity and concomitant "hot spots" in the figures 3.10 and 3.11 are areas near to chicken models.

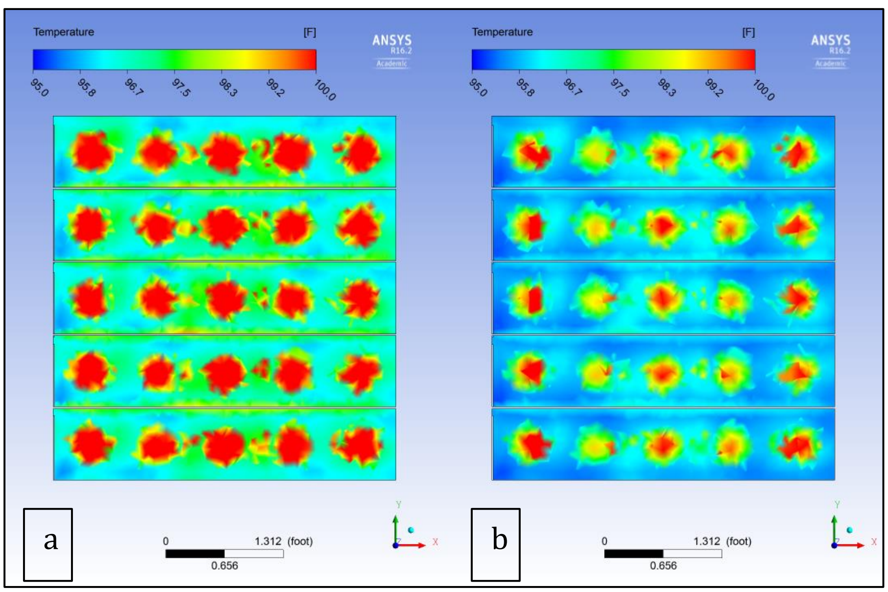

Figure 3.11: Temperature contours for middle plane normal to inlet air of 1.5 m/s (a) and 3.0 m/s (b) and 95° F

Results for the air leaving the back outlet of the module actually show higher velocities (figure 3.12) and lower temperatures (figure 3.13) for air leaving on the door side of the module. These results may be due to the increase in velocity of air as it leaves the narrow gap on the door side of the module.

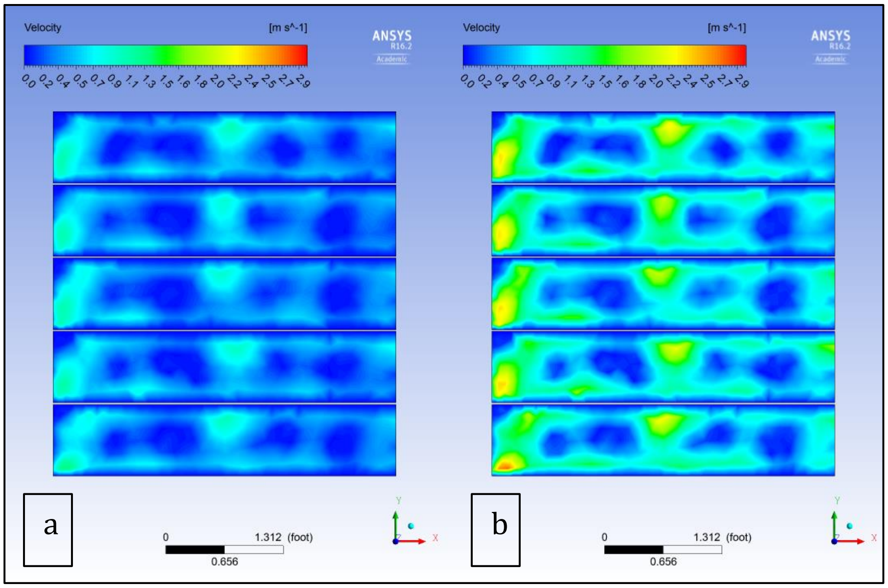

Figure 3.12: Velocity contours for back outlet with inlet air of 1.5 m/s (a) and 3.0 m/s (b). Left sides of each module are the door sides

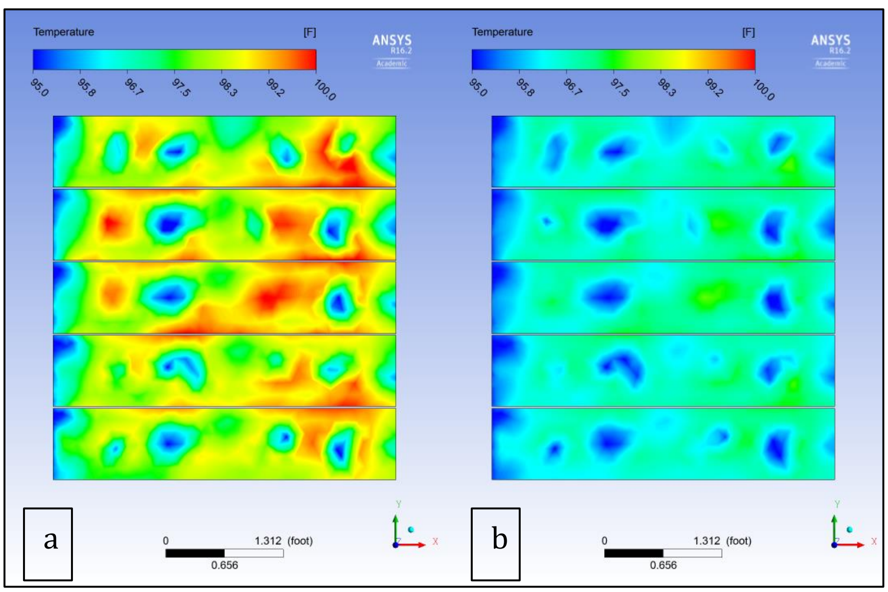

Figure 3.13: Temperature contours for back outlet with inlet air of 1.5 m/s (a) and 3.0 m/s (b) and 95° F

3.2: THVI Results

Table 3.2 – Results for THVI Analysis

Scenario	# of Alert State Points for specified waiting periods			# of Danger State Points for specified waiting periods		
	60 min.	90 min.	120 min.	60 min.	90 min.	120 min.
1	0	0	0	0	0	0
2	0	0	0	0	0	0
3	0	0	1	0	0	0
4	0	0	0	0	0	0
5	2	6	8	0	0	2
6	0	1	1	0	0	0

Table 3.3 – Areas of concern for scenario 5 ($T_{ambient}$ = 95° F, $RH_{ambient}$ = 50%, V_{inlet} = 1.5 m/s)

Point	Temperature (°F)	% RH	Velocity (m/s)	THVI
11	98.4	49.1	0.39	37.5
14	98.2	49.5	0.57	36.6
12	97.7	50.0	0.86	35.5
9	96.5	51.2	0.66	35.4
7	96.4	51.3	0.66	35.4
8	96.4	51.4	0.69	35.3
13	96.8	51.3	0.89	35.0
6	96.2	51.6	0.90	34.7

After simulation of all six scenarios, THVI was calculated for each scenario at each of the 14 chosen points described in Table 3.1. Next, exposure time at each point was calculated based on THVI values for a 1.0°C increase (eq. 4) and a 2.5°C increase (eq. 5). Then, the points were classified as “alert” or “danger” when compared to waiting periods of 60, 90, and 120 minutes. For example, if the exposure time for a 2.5°C increase at a certain point was 55 minutes, then the point would be classified as "danger" for any waiting period longer than 55 minutes.

THVI calculations show that three scenarios (scenarios 3, 5, and 6) exhibited areas of concern for waiting periods of two hours or less. Two of these scenarios had ambient temperature of 95°F, while the other had ambient temperature of 90°F and lower inlet velocity. Scenario 5 showed multiple areas of concern (table 3.3). The highest values of THVI corresponded to a "danger" state in less than two hours; these were points 11 and 14. These points are located in the back end of the trailer, on the side away from the doors, at the bottom and top of the trailer. At these areas, magnitudes of air velocity were approximately 0.4 m/s and 0.6 m/s for points 11 and 14 respectively, leading to higher values of THVI and increased poultry stress. All points located in the middle of the trailer during scenario 5 indicated an "alert" state in 120 minutes or less. Interestingly, point 13 showed a lower value for THVI than three of four middle points despite being located in the back of the trailer. Although temperature was greater at this point than points in the middle, air velocity at this point was greater as well.

An increase in inlet velocity from 1.5 m/s to 3.0 m/s was enough to reduce THVI values significantly from scenario 5 to scenario 6. In scenario 6, only one point corresponded to an "alert" state in two hours or less; point 11. This point as well as point 14 was identified as "danger" points in scenario 5.

These results are not meant to imply that temperatures of less than 95°F will not result in thermal stress on birds. Only ambient conditions of 50% RH were tested, and higher values of relative humidity are common and could cause thermal stress at lower air temperatures.

4. Conclusions and Areas for Future Work

Due to previously mentioned limitations, results from CFD simulations could not be fairly compared to field measurements. Without any validation, this model cannot be considered a valid and accurate representation of actual conditions within a poultry trailer module. The use of a single module necessarily eschews interactions between modules that may be significant. Additionally, more complexity in the definition of boundary conditions and models could be employed to potentially generate a more accurate solution. For the sake of simplicity, this study assumed constant values for heat flux from birds and constant partitioning of latent and sensible heat, in addition to a uniform inlet velocity condition. In actuality, heat generated by the poultry and the fraction of this heat as sensible and latent will vary based on local environmental conditions. Furthermore, inlet conditions into the trailer will vary across the trailer module. Also not considered in this study was the modeling of a misting spray or the application of water directly onto the birds, a practice commonly utilized during hot conditions.

The modeling of birds as explicit spheres at specific locations within the module may prove to not be the most accurate solution. Rather, the modeling of the interior of the module as a homogenous medium with some resistance to airflow may be more appropriate, as the exact position and size of birds is not known at any instant in time anyway. This hypothesis may be tested when more experimental data is acquired from on-site trailers.

Nonetheless, results generated from the model do seem reasonable. The model responded to changes in external temperature and inlet velocity as expected. Along with the THVI, the model predicted areas of concern toward the back of the module. The CFD software used has the ability to rapidly produce comprehensive results and present them in an effective and visually appealing manner. The methodology and software used in this study represent a solid starting point for further development. The end goal of this research work is to fully simulate conditions within an entire poultry trailer and produce results that are accurate compared to measurements taken in the field. The next step in this research is to expand the model to include two trailer modules stacked one on top of the other, and a number of modules side to side. Next, boundary conditions could be adjusted to more accurately simulate real world conditions. If verified with gathered field data, this model could be an asset to poultry scientists to analyze the effect of different environmental conditions on poultry welfare, both for summer and winter, and evaluate different practices for managing poultry heat stress within trailer holding sheds.

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